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Discharge Relations for Rectangular Broad-Crested Weirs

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ABSTRACT

Compound broad-crested weirs have a small inner rectangular section for measuring low flows and then, they broaden to a wide rectangular section at higher flow depths. It can be used as a water measurement device in irrigation canals. This paper presents data that will be of use in the design of hydraulic structures for flow control and measurement. A series of laboratory experiments were performed in order to investigate the effects of width of the lower weir crest and step height of broad-crested weirs with rectangular compound cross section on the values of the discharge coefficient (C_d) and the approach velocity coefficient. For this purpose, 15 different broad-crested weir models with rectangular compound cross sections for a wide range of discharges were tested. The sill-referenced heads at the approach channel and at the tail water channel were measured in each experiment. The dependence of the discharge coefficient and approach velocity coefficient on model parameters was investigated. Results show that a discontinuity occurs in head-discharge ratings because the section width suddenly changes shape, experiencing a break in slope when the flow enters the outer section. Values of C_d obtained from the experiments on compound broad-crested weirs are lower than those of a broad crested weir with a rectangular cross section because of it's contraction effects.

Keywords: Broad-crested weir; Compound; Discharge coefficient; Velocity coefficient

Kalın Eşikli Dikdörtgen Savaklarda Debi İlişkileri

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ÖZET

Bileşik kalın eşikli savaklar, düşük seviyeli akışların ölçümü için küçük bir dikdörtgen bölüme sahiptir ve bu savaklar yüksek akış miktarlarında geniş bir dikdörtgen bölüme doğru genişler. Bu savaklar, sulama kanallarında su ölçüm yapısı olarak kullanılmaktadır. Bu makale, akış kontrolü ve ölçümü için hidrolik yapıların tasarımında kullanılabilecek verileri ortaya koymaktadır. Daha düşük savak eşiği genişliği ve dikdörtgen bileşik kesitli kalın kenarlı savakların düşüm yüksekliğinin, debi katsayısı (C_d) ve yaklaşım hızı katsayısı değerleri üzerine etkilerinin araştırılması amacıyla bir dizi laboratuar denemesi gerçekleştirilmiştir. Bu amaçla geniş aralıklardaki debiler için

15 farklı dikdörtgen bileşik kesitli kalın kenarlı savak modeli test edilmiştir. Yaklaşım kanalı ve çıkış suyu kanalındaki eşik tabanlı yükler her deneyde ölçülmüştür. Model parametreleri üzerindeki debi ve yaklaşım hızı katsayısının bağımlılığı araştırılmıştır. Sonuçlar kesit genişliğinin aniden şekil değiştirmesi ve akışın dış bölüme girdiğinde eğimde bir kırılma olmasından dolayı ana debi oranlarında düzensizlik meydana geldiğini göstermektedir. Bileşik kalın kenarlı savak denemelerinden elde edilen C_d değerleri, daralma etkilerinden dolayı dikdörtgen kesitli kalın kenarlı savaklarınkinden daha düşüktür.

Anahtar sözcükler: Kalın eşikli savak; Bileşik; Debi katsayısı; Hız katsayısı

1. Introduction

A weir is a simple device for discharge measurement and flow control in open channels, such as canals and rivers. The techniques used in making discharge measurements at gaging stations (in rivers, canals, …) are important. The use of portable instrument like kinds of weirs, flumes, floats, and volumetric tank are common. Discharges measured range from a trickle in ditch to a flood on the Amazon.

Many researchers have studied the head-discharge relations for flows over sharp-crested weirs and broad-crested weirs with a simple cross section shape, such as rectangular, triangular, trapezoidal, truncated triangular, and others (French 1986; Ranga Raju 1993; Boiten & Pitlo 1982). Some useful empirical discharge equations for these weirs have been proposed.

A linear combination of traditional discharge equations for simple rectangular and/or triangular weirs is proposed to describe the discharge equations of compound broad-crested (CBC) weirs by Jan et al (2009). The result shows that the differences between the calculated discharges by the proposed equations and the measured ones are less than 3% for flows over these CBC weirs under the experimental conditions.

Based on Sarker & Rhodes (2004) works, measurements of the free-surface profile over a laboratory-scale, rectangular broad-crested weir were performed and were compared with numerical calculations using commercial software. For the given flow rate, the prediction of the upstream water depth was excellent and the rapidly-varied flow profile over the crest was reproduced quite well. In the supercritical flow downstream, a stationary wave profile was observed and reproduced in form by the calculations. Gonzalez & Chanson (2007) conducted experiments in a near full-scale broad-crested weir. Detailed velocity and pressure measurements were performed for two configurations. The results showed the rapid flow distribution at the upstream end of the weir, while an overhanging crest design may affect the flow field. Clemmens et al (1984), studied RBC (Replogle-Bos-Clemmens) broad-crested weirs for circular sewers and pipes. The modified RBC broad-crested weir has many advantages over related open-channel flow devices. These include high accuracy and reliability for a wide variety of shapes, low head-loss requirements which are predictable, and relatively simple inexpensive construction. Based on their investigations, theoretical equations were presented for ideal flow from which approximate ratings can be obtained to within a reasonable accuracy with an empirical discharge coefficient, however, a mathematical model is available which accurately predicts these ratings by directly accounting for the effects of friction. The ratings for a wide variety of shapes and sizes of these weirs were computed with the model and fit to an empirical equation. Design examples are given which show how to select the flume dimensions for maintaining free-flowing conditions (modular flow) and for minimizing sediment deposition.

In practical engineering, a compound weir composed of rectangular parts in the shape of cross section is also a common device for flow control in canals and mountainous gullies (Martinez et al 2005; Jan et al 2006 and Gogus et al 2006). From the view point of construction, the compound weir could be used to measure the flow discharge over the weir providing that the discharge equation of the weir is available.

A broad-crested weir is a flat-crested structure with a crest length large compared to the flow thickness (Figure 1). The ratio of crest length to upstream head over crest must be typically greater than 1.5–3 (Chanson 2004):

$$\frac{L}{H_1} \geq 1.5 - 3 \tag{1}$$

where L is length of the weir crest in the direction of flow; P is broad crested weir height and H_1 is the upstream total head.

When the crest is 'broad' enough for the flow streamlines to be parallel to the crest, the pressure distribution above the crest is hydrostatic and the critical flow depth is observed on the weir crest.

Broad-crested weirs are sometimes used as critical depth meters (*i.e.* to measure stream discharges). The hydraulic characteristics of broad-crested weirs were studied during the 19 and 20th centuries. Hager & Schwalt (1994) recently presented an authoritative work on the topic.

The discharge above the weir equals:

$$q = \frac{2}{3}\sqrt{\frac{2}{3}g(H_1)^3} \tag{2}$$

where g is gravitational acceleration and q is unit discharge.

Equation 2 may be rewritten conveniently as:

$$Q = 1.704\,b(H_1)^{3/2} \tag{3}$$

where Q is total discharge and b is crest width.

Experimental measurements indicate that the discharge versus total head relationship departs slightly from Equation 2 depending upon the weir geometry and flow conditions. Equation 2 is usually rearranged as:

$$q = C_d\frac{2}{3}\sqrt{\frac{2}{3}g(H_1)^3} \tag{4}$$

where C_d is the discharge coefficient and H_1 is upstream total head.

In open channels, it is seldom practical to measure the total energy head, H_1, directly. It is a common practice to relate flow rate to the upstream sill referenced head, h_1, in the following form:

$$q = C_dC_V\frac{2}{3}\sqrt{\frac{2}{3}g(h_1)^3} \tag{5}$$

where C_v is the approach velocity coefficient, which corrects for neglecting the velocity head at the measurement section.

According to Horton (1907), the discharge coefficient depends exclusively on the relative weir length H_1/L, provided effects of viscosity and surface tension may be neglected. For water, the typical limit head H_L is some 30-50 mm. For $H_1>H_L$, the discharge coefficient may be expressed for the so-called confined weir.

For $H_1/L\rightarrow 0$, the asymptotic discharge coefficient is C_{do}=0.326. A distinct feature of the broad-crested weir is the corner separation, which was analyzed by Keutner (1934) & Moss (1972). Its length was found to be 0.77h_o, and its maximum height is 0.15h_o (h_o is the water depth on weir crest). Tracy (1957) was able to generalize the surface profile using h_o as normalizing parameter, provided $0.1<H_1<0.4$.

According to Singer (1964) the effect of weir height H_1/P may be neglected if $H_1<P/2$. Further, a number of limits concerning the approach flow depth, channel width, weir height, and crest length were specified. Ranga Raju & Ahmad (1973) studied the broad-crested weir in both the prismatic and the converging channel. Crabbe (1974) expanded the application limits as proposed by Singer (1964) in terms of weir length and weir height. For large values of P, aeration of the lower nappe is essential, and a significant advantage of the broad-crested weir is dropped.

According to Ramamurthy et al. (1987) the upstream corner of a broad-crested weir may be considered sharp provided the radius of curvature is smaller than $R<0.094P$. Thus, extreme sharpness of corner radius on the flow is not necessary.

The purpose of this study is to investigate discharge coefficient (C_d) in compound rectangular broad-crested weirs with different geometry dimension like: step heights (z), weir

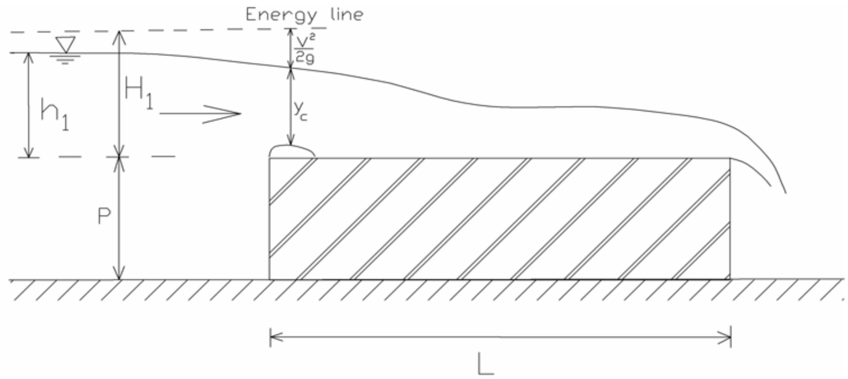

Figure 1-Flow pattern above a broad-crested weir

Şekil 1-Bir kalın eşikli savak üstündeki akış rejimi

widths (b) and weir lengths (L) using experimental physical models. Effect of flow contraction due to installation of weirs in the flume is investigated for C_d too. In addition comparisons of present results with other researchers study have been carried out. Finally proper relations for estimating of C_d are presented.

2. Material and Methods

The experiments were conducted at the hydraulic laboratory at Tabriz University, in IRAN. The experiments were conducted in a horizontal rectangular channel 25 cm wide and 70 cm high with vertical plexiglas sides. The total length of channel was some 12 m, with the front side of glass, and the bottom and back side of black PVC. The compound broad-crested weirs of height P=10, 13 and 16 cm; length L=30, 35 and 40 cm; lower weir crest width b=6, 8 and 12 cm and step height of model cross section z=9 cm were built (15 physical modes) and were located at 5 m downstream of the inlet, and various elements to improve the approach flow were provided upstream of the weir (Table 1). Thus, an excellent, smooth, and wave less flow was obtained that could be analyzed accurately.

The upstream corner of all compound broad-crested models was rounded with the radius of curvature R_1, R_2 and R_3 in Table 1. The tail water submergence was adjusted by a flap gate located at the channel end 12 m from the inlet. The discharge was measured with a 53°notch to the nearest 0.1 mm in head.

Surface profiles were observed with a precise point gauge (±0.1 mm). Particular attention was paid to standing wave patterns at low overflow depth, and it was important to collect accurate surface readings.

Six pressure taps were located along the centerline of weirs, with spacing 5 cm from each other. Physical models were built from with conventional PVC. The upstream corner had rounded surface. An estimated radius of curvature (R_1 and R_2) was about 5 cm. The pressure taps were connected with a manometer battery where bottom pressure could be read to ±0.5 mm. In general, the oscillations in the manometer tubes were less than ±1 mm. Figure 2 shows definition sketch of models used in theoretical analysis.

For broad-crested weirs of rectangular compound cross section, there are two different cases to be analyzed, as shown in Figure 3.

Case 1: $H_1 \leq 1.5Z$, $y_c \leq Z$

When the flow depth is less than lower weir crest height (Z), weir works like traditional broad crested (or simple not compound shape). In this case, total energy at upstream of weir will be less than 1.5Z. For Case 1, flow occurs only through the lower weir crest part of the compound cross section. For this case, the equation of discharge can be obtained as Equation 6:

Table 1-Models used in experiments

Şekil 1-Deneylerde kullanılan modeller

Model no	L, cm	B, cm	b, cm	R_1, cm	R_2, cm	R_3, cm	P, cm	Z, cm
1	40	25	12	5	5	6.5	16	9
2	40	25	8	5	5	8.5	16	9
3	40	25	6	5	5	9.5	16	9
4	40	25	12	5	5	6.5	13	9
5	40	25	8	5	5	8.5	13	9
6	40	25	6	5	5	9.5	13	9
7	40	25	12	5	5	6.5	10	9
8	40	25	8	5	5	8.5	10	9
9	40	25	6	5	5	9.5	10	9
10	35	25	12	5	5	6.5	10	9
11	35	25	8	5	5	8.5	10	9
12	35	25	6	5	5	9.5	10	9
13	30	25	12	5	5	6.5	10	9
14	30	25	8	5	5	8.5	10	9
15	30	25	6	5	5	9.5	10	9

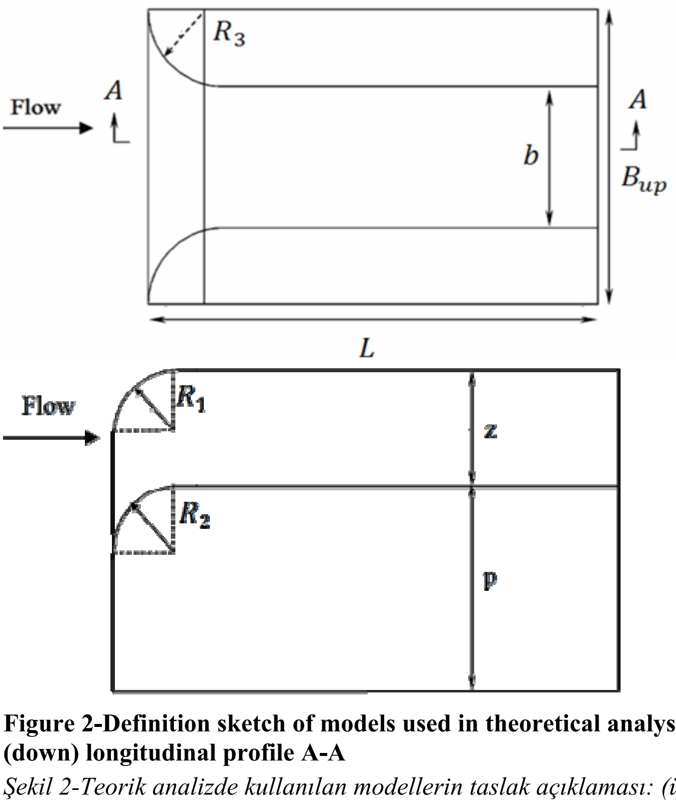

Figure 2-Definition sketch of models used in theoretical analysis: (up) plan view; (down) longitudinal profile A-A

Şekil 2-Teorik analizde kullanılan modellerin taslak açıklaması: (üstte) plan görünümü, (altta) A-A boyuna kesit

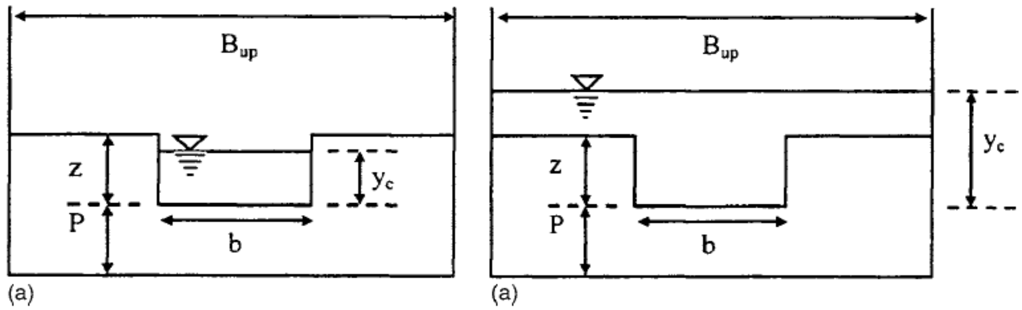

Figure 3-Two different flow cases through weir section: (a) Case 1; (b) Case 2

Şekil 3-Savak kesitinden geçen iki farklı akış durumu (a) Durum 1; (b) Durum 2

$$Q = C_d C_V \frac{2}{3} b \sqrt{\frac{2}{3} g (h_1)^3} \quad (6)$$

From equations 4 and 6, we have:

$$C_d = \frac{3}{2} . \frac{Q}{b(2g/3)^{1/2} H_1^{3/2}} \quad (7)$$

$$C_v = \left(\frac{H_1}{h_1} \right)^{3/2} \quad (8)$$

Case 2: $H_1 > 1.5Z$, $y_c > Z$

In this case, flow occurs through the compound cross section, so that the depth at the control section, i.e., the critical depth, is greater than Z. The wetted area of the flow at the control section is:

$$A_c = bz + (y_c - z) B_{up} \quad (9)$$

where B_{up} is top width of the head measurement section and of the weir model cross section (*up*=upstream) in Figure 3. For this case, the equation of discharge can be obtained as Equation 10:

$$Q = C_d C_V \left(\frac{g}{B_{up}}\right)^{1/2} \left[bz + B_{up} (2/3 H_1 - \frac{bz}{3B_{up}} - \frac{2z}{3}) \right]^{3/2} \quad (10)$$

Again for C_d and C_v we have:

$$C_d = \frac{Q}{\left(\frac{g}{B_{up}} \right)^{1/2} \left[bz + B_{up} \left(\frac{2}{3} H_1 - \frac{bz}{3B_{up}} - \frac{2z}{3} \right) \right]^{3/2}} \quad (11)$$

$$C_v = \left(\frac{bz + B_{up} \left(\frac{2}{3} H_1 - \frac{bz}{3B_{up}} - \frac{2z}{3} \right)}{bz + B_{up} \left(\frac{2}{3} h_1 - \frac{bz}{3B_{up}} - \frac{2z}{3} \right)} \right)^{3/2} \quad (12)$$

3. Results and Discussions

3.1. Head-discharge rating

In Figure 4, head-discharge rating data for different values of P=10, 13 and 16 cm have been presented. Figure 4 shows that variation of weir height has not significant effect on head-discharge rating and in fact head-discharge rating in three data set (P=10, 13 and 16 cm) coincide together and have a same trend line. Figure 4 is based on 38 point data.

In compound structures, it is expected that there is always a discontinuity in the head-discharge rating at the boundary between Cases 1 and 2. A discontinuity occurs because the section width suddenly changes shape. The area function for the throat is discontinuous, and thus the resulting discharge curve should also be discontinuous, experiencing a break in slope when the flow enters the outer section. Therefore, the compound weirs/flumes are designed with sloping expansions to reduce this transition zone. As expected, the discontinuities in the ratings occur at about h_1=1.5z=1.5(9)=13.5 cm, where z is the depth of the inner section (z=9 cm). This head corresponds to a critical depth, y_c, which completely fills the inner section.

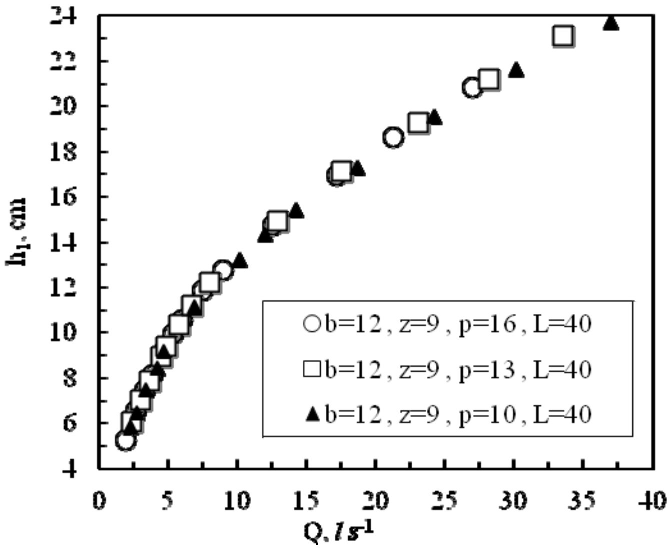

Figure 4-Head-discharge curves for various weir height (*P*)

Şekil 4-Çeşitli savak yükseklikleri için ana debi eğrileri

The discontinuity in the rating of the models b=12, z=9 and L=40 cm is clearly evident (Figure 4), because the rating curves trend line, change from about h_1=13.5 cm. This discontinuity did not see in Gogus et al. (2006) studies.

In Figure 5, head-discharge curves for various crest width were presented. For the same h_1, increasing in b, results in increasing at Q. Again the discontinuity in the rating of the models is clearly evident, because the rating curves trend line change from about h_1=1.5z =13.5 cm. Comparison between Figures 4 & 5, demonstrate that variation of weir height from 10 to 16 cm, have not any significant effect on head-discharge curves and in contrast variation of crest width from 6 to 12 cm changes head-discharge curves. Thus for each crest width, individual head-discharge curve needed. In Figure 5, three different curves must be fitted for head-discharge relationship.

In Figure 6, head-discharge curves for various crest length were presented. There is no significant effect of L on head-discharge curves. In fact increasing of L from 30 to 40 cm has very little effect on resistant due to friction. So all data points for 3 values of L, coincide on each another. Note that in the all selected range for crest length, definition criteria by Equation 1, ($L/H_1 \geq 1.5$-3) is valid. Therefore for practical purposes, no any head-discharge curves variation occurs when making with different crest length, satisfied in Equation 1.

3.2. Discharge coefficient

The effect of the lower weir crest width and height of weir crest/sill on the discharge coefficient is investigated by comparing the C_d values obtained from the experiments carried out on the models with varying b or P and constant z and L. The values of C_d for three different values of b and P were plotted as a function of H_1/L, keeping the z and L constant in Figure 7.

In Gogus et al (2006) study, values of C_d in all models (with different b) are almost coincident, particularly when H_1/L values exceed 0.30. In contrast with Gogus et al (2006), no divergence for H_1/L<0.30 can be distinguish for models of b=6, 8 and 12 cm in Figure 7. Although for H_1/L>0.27, data trend line was changed and the same line can be fitted for b=6, 8 and 12 cm. This

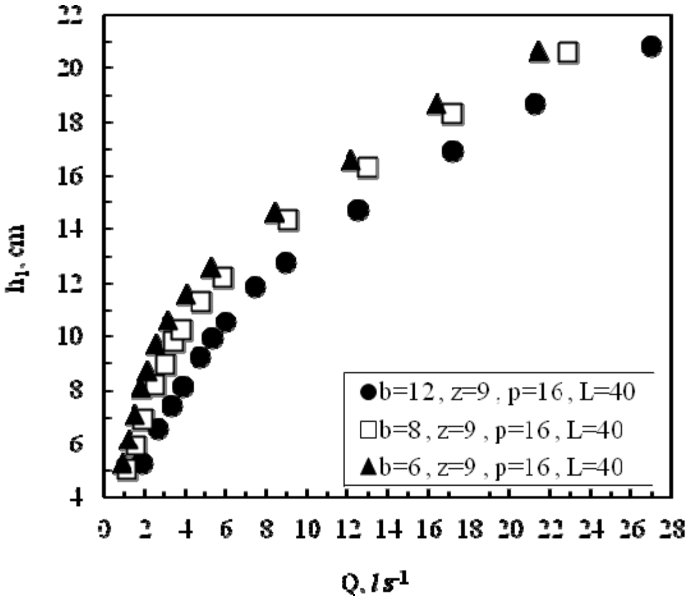

Figure 5-Head-discharge curves for various crest width (*b*)
Şekil 5-Çeşitli eşik genişlikleri için su ana debi eğrileri

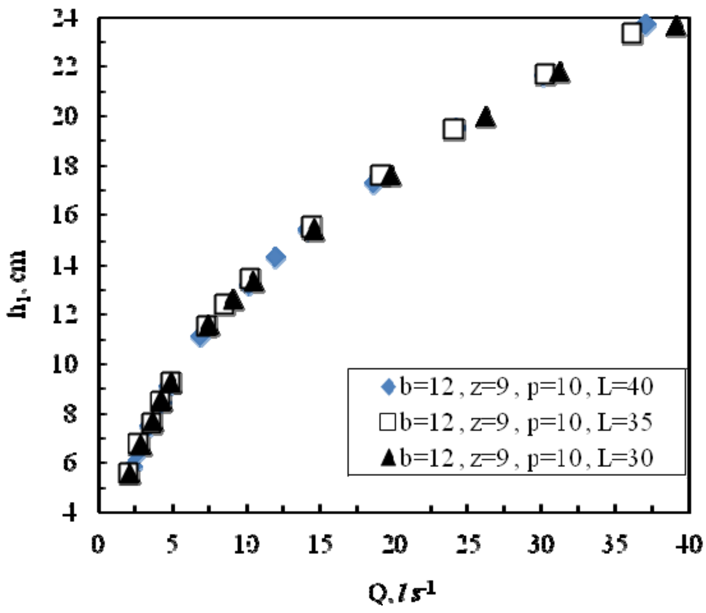

Figure 6-Head-discharge curves for various crest length (*L*)
Şekil 6-Çeşitli eşik uzunlukları için ana debi eğrileri

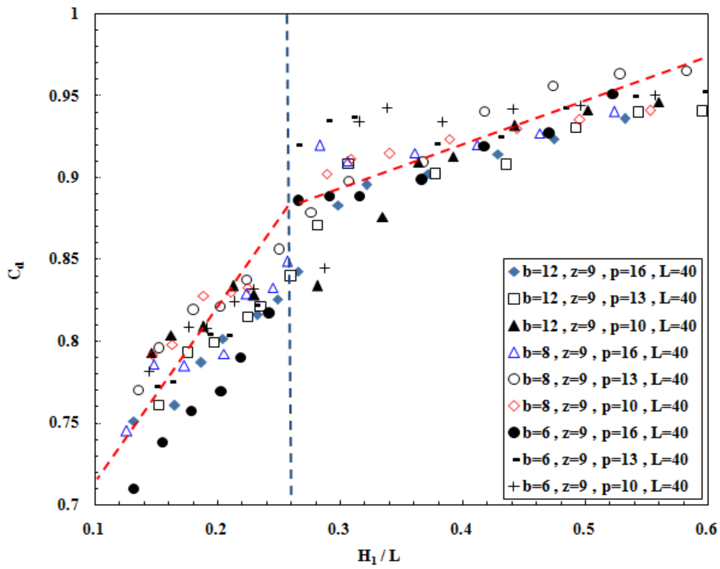

Figure 7-C_d versus H_1/L for varying *P* and *b* and constant *z* and (*L*)

Şekil 7-Değişen P ve b ve sabit z ve L için C_d-H_1/L grafiği

demonstrates that discontinuity occurs because the section width suddenly changes shape.

In fact, we can say that C_d normalized with *b* in Figure 7 referring to Equations 7 and 11 for calculation for C_d. So we will not have 3 trend line as Figure 5, for 3 values of *b*. Significant variation of *b* (like Figure 5), was imported to C_d (normalized) by Equation 7 and 11 and this does not exist in Gogus et al (2006) study.

Like Figure 4, variation of weir height has not significant effect on head-discharge rating and three data set (*P*=10, 13 and 16 cm) coincide together and have the same trend line.

In Figure 7, two linear Equations 13 and 14 can be fitted for two trend lines belongs to Cases 1 and 2 (Figure 3), as follows:

$$C_d = H_1/L + 0.612 \quad For \quad H_1/L \leq 0.27 \tag{13}$$

$$C_d = 0.309(H_1/L) + 0.796 \quad For \quad H_1/L > 0.27 \tag{14}$$

Determination coefficients for two represented lines for lower and upper part of compound broad-crested weirs in Figure 7 are 0.879 and 0.904 for Equations 13 & 14, respectively.

In Table 2, equations used by other researcher for C_d in broad crested weir were presented. Comparison among these equations with present study (compound broad crested weir) was shown in Figure 8. The discharge coefficient values obtained from the experiments were performed on the compound broad-crested weirs are lower than those of a broad crested weirs with a rectangular cross section for H_1/L<0.27. Although the models entrance in this study is rounded, but this reduction in C_d is probability due to contraction of flow by weir cross section.

Comparison among C_d versus H_1/L in present study (b=6, 8 and 12 cm) with Gogus et al (2006) were shown in Figure 9. The discharge coefficient values obtained from both the experiments are well agreed.

In Figure 10, variation of velocity coefficient, C_V, has been presented. This Figure is based on Equations 8 & 12 discussed previously. In Figures 10, for H_1/L>0.26, three different line can be fitted to data points, but for H_1/L<0.26, all three data set points converge each other. This result agrees

Table 2-Equations used by other researcher for C_d in broad crested weir

Çizelge 2-Kalın kenarlı savaklarda C_d (debi katsayısı) için diğer araştırmacılar tarafından kullanılan eşitlikler

Name of researcher	*Equation*	*Condition*
French (1987)	$C_d = (1 - 2x(L-r)/T) * (1 - x(L-r)/T)$	$0.08 < (H_1 / L) < 0.33$ $H / (H_1+P) < 0.35$ Broad crested weir with rounded entrance
Muralidhar and Govinda Roa (1963)	$C_d = 0.913 + 0.049(H_1 / L)$	$0.1 < (H_1 / L) < 0.35$ With viscosity effect
Muralidhar & Govinda Roa (1963)	$C_d = 0.971(H_1 / L)^{0.022}$	$0.1 < (H_1 / L) < 0.35$ Without viscosity effect
Bos (1976)	$C_d = (1 - 0.01(L_t - r)/W) * (1 - 0.01(L_t - r)/(d_1 - Z))$	$(d_1 - z) / L > 0.05$ $(H_1 - Z) / Z < 1.5$ Broad crested weir with rounded entrance
Azimi & Rajaratnam (2009)	$C_d = 0.9 + 0.147(H_1 /(H_1 + P))$	$0.1 < (H_1 / L) < 0.4$ Broad crested weir with rounded entrance

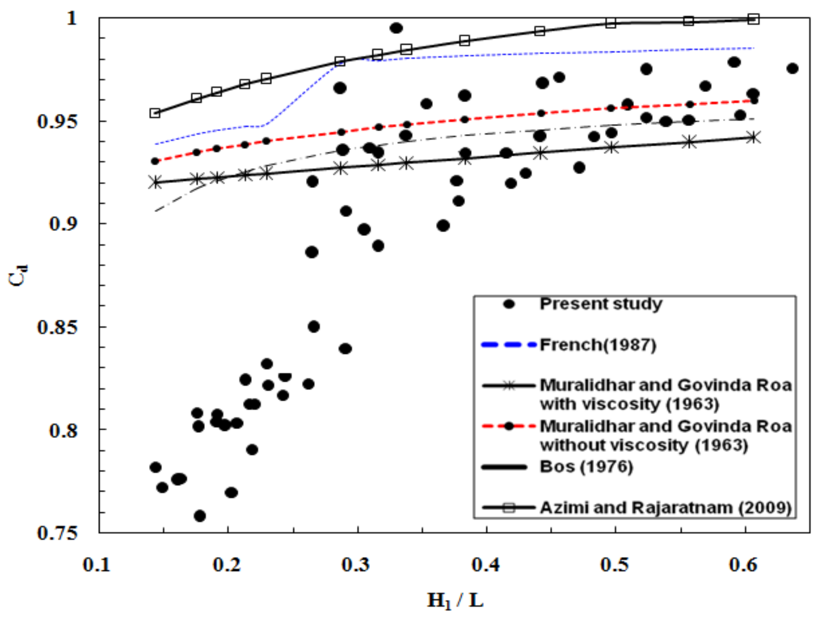

Figure 8-Comparison among Cd versus H_1/L in present study and others

Şekil 8-C_d-H_1/L ilişkisinin bu çalışma ile diğer çalışmalar arasındaki karşılaştırması

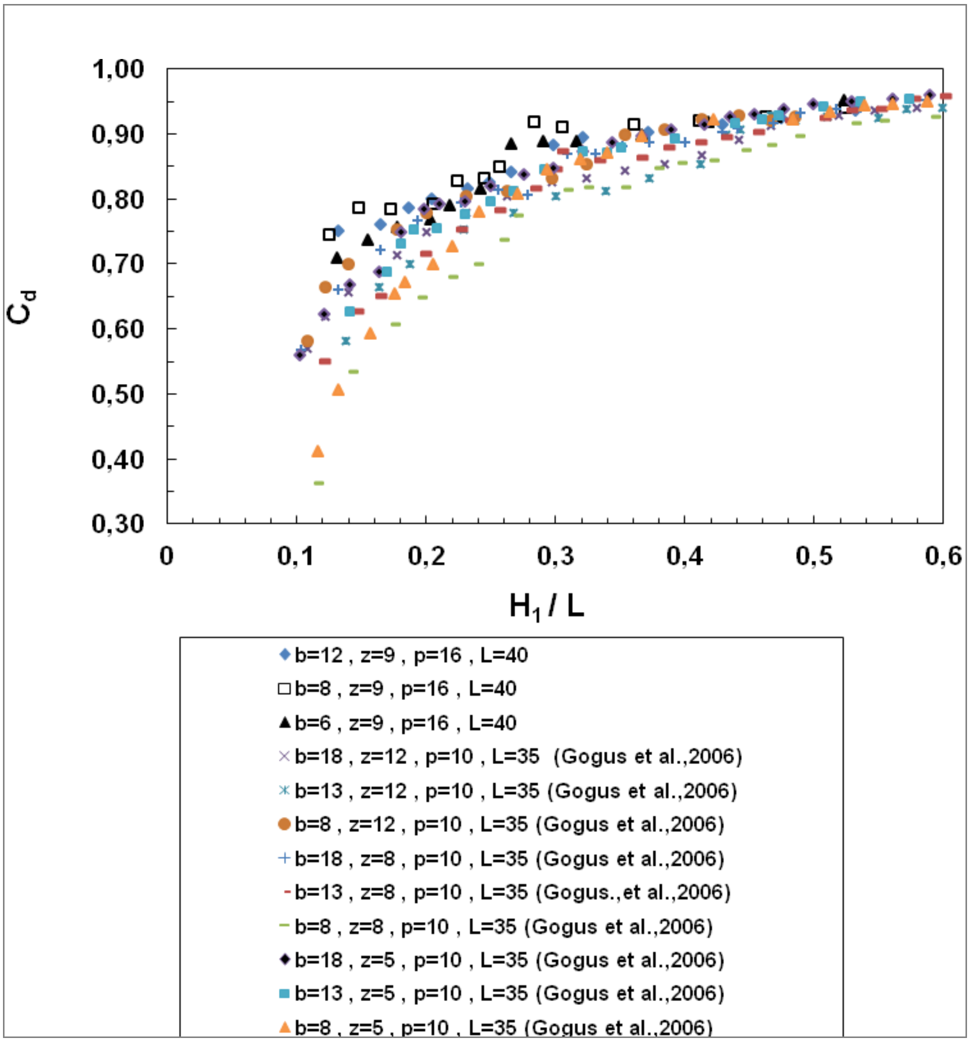

Figure 9-Comparison among *C*d versus H_1/L in present study with Gogus et al (2006)

Şekil 9-Cd-H1/L ilişkisinin bu çalışma ile Gogus et al. 2006 yapılan çalışma arasındaki karşılaştırması

with Equations 8 and 12 which show C_V for case 1 and 2. In Equation 8, parameter *b* does not exist and so all point data lay each other. In equation 12, parameter *b* does exist and so three lines can be drawn (Case 2). Note that this result differs with C_d values in different *b*, previously illustrated in Figure 7.

4. Conclusions

The discontinuity in the weir ratings is clearly evident. Effect of weir height can be ignored when calculate C_d, and the effect of weir width exist implicitly in C_d. So application of Equations 13 & 14 will have proper results for C_d. The discharge coefficient, C_d , tends to

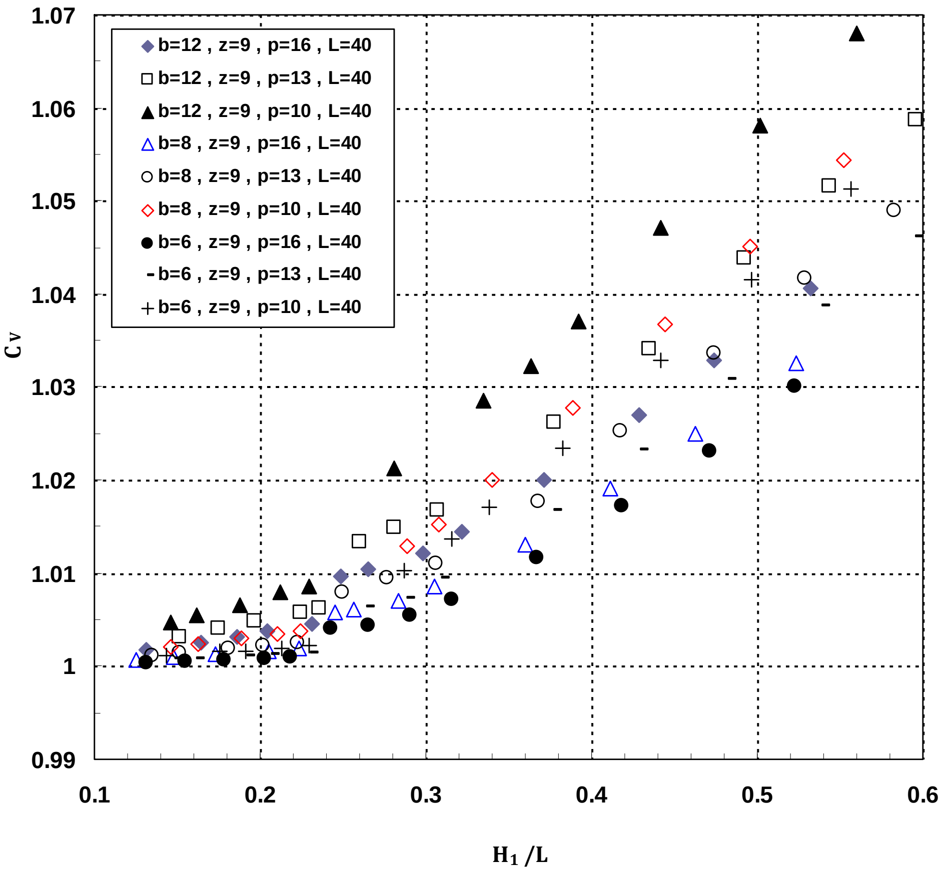

Figure 10-CV versus H_1/L for varying *L* and *P*; constant *z* and *L*

Şekil 10-Değişen L ve sabit z ve L değerlerinde CV-H_1/L grafiği

increase when H_1/L increases, particularly two linear equation (Equation 13 & 14) can be defined for left and right boundary in H_1/L=0.27 point. In left boundary of point H_1/L=0.27, flow occurs only through the lower weir crest part of the compound cross section (Case 1) and Equation 13 is satisfied. In right boundary of H_1/L=0.27, (Case 2), Equation 14 is satisfied. Values of C_d obtained from the experiments were performed on the compound broad-crested weirs are lower than those of a broad crested weir with a rectangular cross section for H_1/L<0.27 because of its contraction effects. Calculating of velocity coefficient, C_V, show that for H_1/L>0.26, three different line can be fitted to data points, but for H_1/L<0.26, all three data set points converge each other.

Notation

A_c=cross-sectional area at control section;
B_{up}=top width of head measurement section and weir model cross section;
b=lower weir crest width of model;
C_d =discharge coefficient;
C_v=approach velocity coefficient;
g=acceleration of gravity;

H_1=total energy head at upstream head measurement section;
h_1=head at upstream head measurement section;
L=length of weir crest in direction of flow;
P=height of weir crest (sill);
Q=volumetric rate of flow;
R_1=rounding at entrance of lateral contraction resulting from lower weir crest part of weir crest cross section;
R_2=rounding at entrance of weir at top of step of weir crest cross section;
y_c=critical water depth at control section;

References

Azimi A H & Rajaratnam N (2009). Discharge characteristics of weirs of finite crest length. *Journal of Hydraulic Engineering* **135**(12):120-125

Boiten W & Pitlo H R (1982). The V-shaped broad-crested weir. *Journal of Irrigation and Drainage Engineering* **108**(2): 142-160

Bos M G (1976). Discharge measurement structures, 2nd Ed., *International Institute for Land Reclamation and Improvement*, Wageningen, The Netherlands

Clemmens A J, Bos M G & Replogle J A (1984). RBC broad-crested weirs for circular sewers and pipes. *Journal of Hydrology* **68**: 349-368

Crabbe A D (1974). Some hydraulic features of the square-edged broad-crested weir. *Water and Water Engineering* **78**(10): 354-358

French R H (1987). Open-channel hydraulics. McGraw-Hill, New York

Gogus M & Oskandemir V (2006). Broad-crested weirs with rectangular compound cross section. *Journal of Irrigation and Drainage Engineering* **132**(3): 272-280

Gonzalez C A & Chanson H (2007). Experimental measurements of velocity and pressure distributions on a large broad-crested weir. *Flow Measurement and Instrumentation* **18**:107-113

Hager W H & Schwalt M (1994). Broad-crested weir. *Journal of Irrigation and Drainage Engineering* **120**(1): 13-26

Harrison A J M (1967). The streamlined broad-crested weir. *Proceedings of the Institution of Civil Engineers* **38**: 657-678

Horton R E (1907). Weir experiments, coefficients, and formulas. Dept. of the Interior, U.S. Geological Survey, Water-Supply and Irrigation Paper 200. Government Printing Office, Washington, D.C

Keutner C (1934). Strrmungsvorginge an breitkronigen Wehrkrpern und an Einlaufbauwerken. Bauingenieur, 15(37/38), 366-371; 15(39/40), 389-392 (in German)

Jan C D, Chang C J & Kuo F H (2009). Experiments on discharge equations of compound broad-crested weirs. *Journal of Irrigation and Drainage Engineering* **135**(4): 61-73

Jan C D, Chang C J & Lee M H (2006). Discussion of 'Design and calibration of compound sharp-crested weir, by J. Martinez et al. *Journal of Hydraulic Engineering* **132**(8): 868-871

Martinez J, Reca J, Morillas M T, & López J G (2005). Design and calibration of a compound sharp-crested weir. *Journal of Hydraulic Engineering* **131**(2): 112-116

Moss W D (1972). Flow separation at the upstream edge of a square-edged broadcrested weir. *Journal of Fluid Mechanics* **52**(2): 307-320

Ramamurty A S, Udoyara S T, & Rao M V J (1987). Characteristic of square-edged and round-nosed broad-crested weirs. *Journal of Irrigation and Drainage Engineering* **114**(1): 61-73

Ranga Raju K G 1993. Flow through open channel, McGraw-Hill, New York

Ranga Raju K G & Ahmad I (1973). Discharge characteristics of suppressed and contacted broad-crested weirs. *Journal of Irrigation and Power (India)* **30**(4): 157-166

Sarker M A & Rhodes D G (2004). Calculation of free-surface profile over a rectangular broad-crested weir. *Flow Measurement and Instrumentation* **15**(4) 215-219

Singer J (1964). Square-edged broad-crested weir as a flow measurement device. *Water and Water Engineering* **68**(6): 229-235

Tracy H J (1957). Discharge characteristics of broad-crested weirs. *U.S. Dept. of Interior*, Geological Survey Circular 397, Washington D.C